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Assessment of rice self-sufficiency in 2025 in eight African countries

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Abstract

Most African countries are far from self-sufficient in meeting their rice consumption; in eight countries the production: consumption ratio, ranged from 0.16 to 1.18 in 2012. We show that for the year 2025, with population growth, diet change and yield increase on existing land (intensification), countries cannot become fully self-sufficient in rice. This implies that for the future, a mixture of area expansion and imports will be needed on top of yield gap closure. Further research is needed for identification of most suitable new land for rice area expansion and areas that should be protected.

Keywords: food security, population, rice, yield gap, yield potential, Africa

1. Introduction

Faced with a growing population and increasing per capita rice consumption, countries and their policy makers have three options to meet future demand for rice: increase imports, increase rice area and increase production per unit area. Often, growing needs are met through a combination of these three options. But in some cases one or more of these solutions are not possible, or only to a limited extent. Such is the case when biophysical limits to yield increase have been reached, or where all of the suitable land is already being used for agriculture or cultivation of specific crops. It is therefore relevant to quantify the biophysical opportunities and limits. Many African politicians have formulated ambitious plans for increasing production (Seck et al., 2012, 2013; <http://www.riceforafrica.org>). It is therefore timely to investigate the quantitative relationship between self-sufficiency or import levels on the one hand and yield gap closure and area expansion on the other hand. We do not make (political or societal) statements on which mixture of imports, area expansion and yield increase is most desirable or most realistic politically. Rather, we compute the window of opportunities between these key variables. Rather we aim to quantify trade-offs between imports and area expansion for rice cultivation. These trade-offs depend on uncertain future trends in per capita consumption and yield increase.

We therefore present different scenarios to quantify the range of possible outcomes. Such an analysis is also relevant in the context of studies on “intensification” (raising yields on existing fields through yield gap closure). Most recent studies consider intensification the most desirable option, due to concerns about land availability and quality, and the need to protect natural ecosystems (Tilman et al., 2002; Cassman et al., 2003; Koning and van Ittersum, 2009; Foley et al., 2011; Pretty et al., 2011; Ramankutty and Rhemtulla, 2012; Garnett et al., 2013; Hall and Richards, 2013).

In Africa, with its rapid population growth, agricultural area has been expanding and is likely to continue. This expansion has occurred because yield increase on existing land has been too slow to keep up with growing consumption in most African countries (Pretty et al., 2011). The future required agricultural area can be estimated based on extrapolation of current trends in yield and consumption (e.g. Balmford et al., 2005). Such approaches have been criticized (e.g., van Ittersum et al., 2013) because such extrapolations may lead to yield projections above the biophysical upper limits imposed by solar radiation, temperature, and water supply (which is impossible). Quantification of the biophysical upper limits to yield increase through the use of crop growth models may help more realistic quantification of the extent to which self-sufficiency can be achieved through intensification.

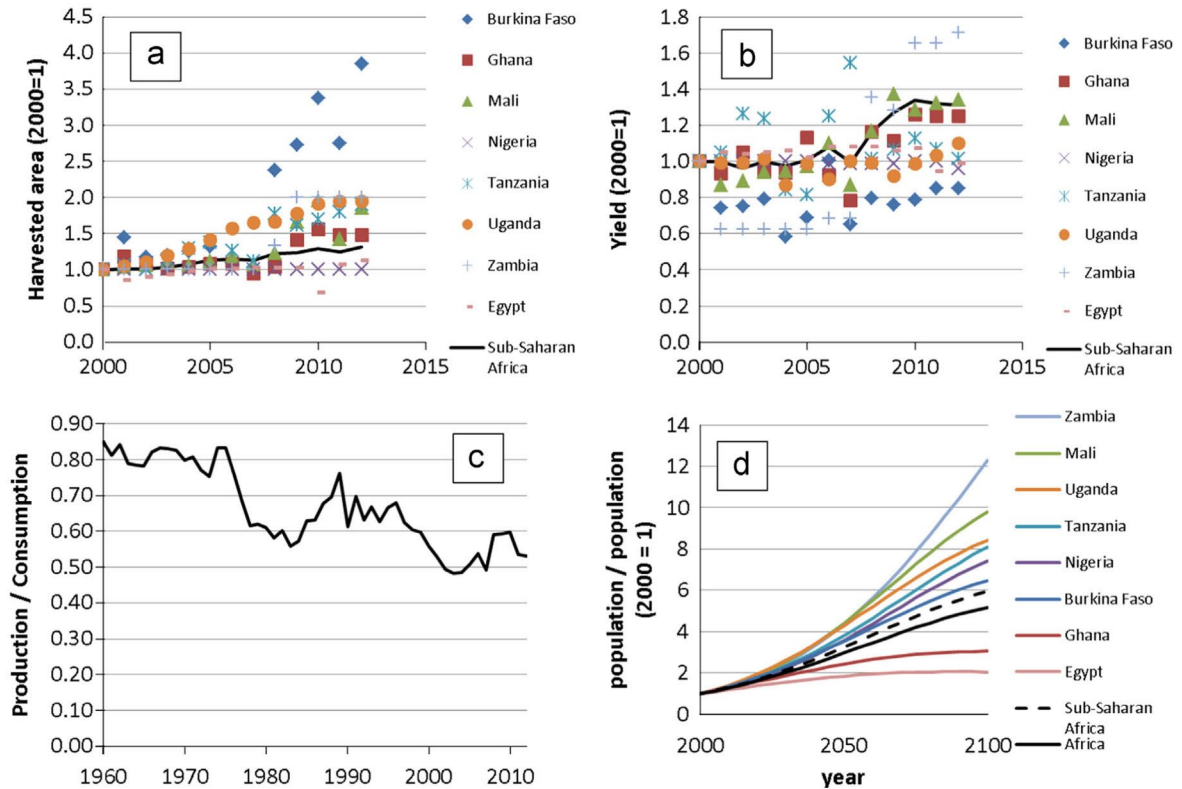


Figure 1. Trends in harvested area (a), yield (b), production/consumption (c) and population (d). (Based on USDA, 2014 and UN, 2014).

Since 2000, both rice harvested area and yield have been increasing in Sub-Saharan Africa (SSA) (Figures 1a and 1b). However, the ratio between production and consumption (P/C ratio), which is an indicator for self-sufficiency, has been far below one for a considerable time (Figure 1c), indicating that most countries in SSA are still far from being self-sufficient in rice. Meanwhile, the population (UN, 2014, Figure 1d) and per-capita consumption are expected to continue to increase. If growth in yields cannot keep track of growth in consumption then either more area, more imports, or a combination of these two will be needed.

With a growing population and changing diets policy makers have basically three options to meet future consumption needs: (1) increase yields, (2) increase imports and (3) area expansion. A conceptual model of the decision-making space is shown in Figure 2. For a given population and at given yield levels and diet, any linear combination of area and imports can fulfill the population's needs. If population grows or if per capita consumption grows, then either more imports or more area will be needed. If yields increase then less imports or less area will be needed. The area in between the dashed lines shows the biophysical boundaries within which choices are made. These lines are dashed because they reflect uncertainty about future trends in population growth, diet change and yield increase. There is a clear trade-off between the political choice to reduce imports (which may require further area expansion) and the political choice to reduce area expansion (and remain dependent on international markets for imports). The biophysical boundaries within which this economic, societal and political decision making will take place are still not well quantified.

The objective of this paper is to quantify the trade-offs between area expansion and import dependency at different levels of yield increase and diet change. We present scenarios for the year 2025 for eight African countries. We choose this relatively near time horizon since it is meaningful for most African

policy makers. The objective of this study is to assess self-sufficiency scenarios with a longer time horizon suffer from increased uncertainty of population growth scenarios (Hopfenberg and Pimentel, 2001; Alexandratos, 2005; Dyer, 2013), increased uncertainty in estimates of available area (Andriess, 1986; Windmeijer and Andriess, 1993; Young, 1999; Ramanakutty et al., 2002; You et al., 2011; Byerlee et al., 2014), and uncertainty about climate change impacts (which for rice in Africa have not yet been clearly quantified). The choice of seven SSA countries was driven by the Global Yield Gap Atlas project (GYGA, <http://www.yieldgap.org>) on which the results presented here are based. Egypt was included as a benchmark for an African country where yield gaps are expected to be small.

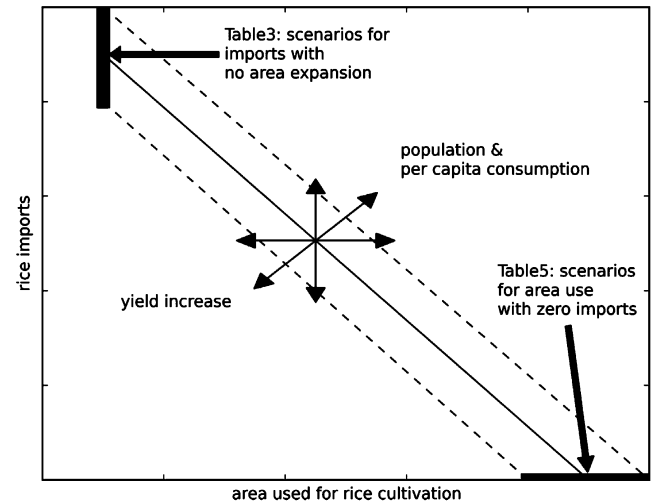


Figure 2. Conceptual model of trade-offs between area and imports, with effects of yield increase, population growth and growth in per capita consumption.

2. Methods

We first describe a framework used for calculating rice self-sufficiency at the national level in the eight countries (Burkina Faso, Egypt, Ghana, Mali, Nigeria, Tanzania, Uganda, and Zambia). We describe the method of selection of sites at subnational level, an approach used for calculations of actual and potential yields in each site, and input data used for the calculations. The actual and potential yields estimated at the subnational level were aggregated to the national level. We then provide the calculation methods for rice harvested area and consumption at national level.

2.1. Rice self-sufficiency

Self-sufficiency calculations can be reduced to a simple equation of production and consumption. We use the production-consumption ratio (P/C) as an indicator of self-sufficiency, where a country is self-sufficient at $P/C=1$. Production depends on harvested area and yield, consumption depends on population and per-capita consumption. For a given consumption, we can calculate what harvested area and yield levels are needed to make production meet consumption. Total rice production for a country was calculated as

$$P_{unmilled} = HA_{rf} \times Y_{rf} + HA_{ir} \times Y_{ir} \quad (1)$$

where $P_{unmilled}$ is production (thousands of tons) of unmilled rice; HA_{rf} and HA_{ir} are harvested areas of rainfed and irrigated rice (thousands of hectares); Y_{rf} is the yield of rainfed rice (t/ha unmilled rice, at 14% moisture content); and Y_{ir} is the same for irrigated rice. Three yield levels (Y_a , Y_w , and Y_p) are considered:

Y_a	current average yield of unmilled rice, with $Y_{a_{rf}}$ and $Y_{a_{ir}}$ for rainfed and irrigated systems, respectively.
Y_p	yield potential, determined by temperature and solar radiation during the crop production period, assuming no limitations on water or nutrient supply and no loss of yield to toxicities, insects or other herbivores, diseases, or weeds; Y_p was used as the benchmark for irrigated rice.
Y_w	water-limited yield potential, governed by temperature, solar radiation, rainfall, soil properties, and landscape position that govern root-zone water-holding capacity and runoff, assuming no limitations on crop yield due to nutrient deficiencies, toxicities, insects or other herbivores, diseases, or weeds; Y_w was used as the benchmark for rainfed rice.

From these we calculated absolute yield gaps ($Y_p - Y_{a_{ir}}$ for irrigated rice and $Y_w - Y_{a_{rf}}$ for rainfed rice) and relative yields $Y_{a_{ir}}/Y_p$ and $Y_{a_{rf}}/Y_w$. The distinction between irrigated rice and rainfed rice is important because actual yields and yield potential are much higher in irrigated rice. Within rainfed rice a distinction was made between rainfed upland and rainfed lowland. Rainfed upland soils are generally located higher in the landscape, have stronger drainage, and deeper groundwater levels in comparison with lowland. Soil fertility is often lower in upland soils compared to the lowlands. We calculated Y_w separately for upland and lowland conditions and then aggregated to rainfed Y_w values using the relative areas of upland and lowland rice area at each site (site selection and aggregation to national level is described in Section 2.2).

Total rice consumption is normally expressed in kilograms of milled rice. In rice milling, the husk and bran layers are removed to reveal the edible, white rice kernel. In this process, depending on the quality of the unmilled rice and the mills, 30–40%

of the weight is removed. We calculated milled production as

$$P_{milled} = 0.65 \times P_{unmilled} \quad (2)$$

Domestic consumption or consumption depends on population (expressed in millions) and per-capita consumption (kg person⁻¹ year⁻¹)

$$C_{milled} = \text{Population} \times \text{Per capita consumption} \quad (3)$$

where D_{milled} is domestic consumption for milled rice (thousands of tons). In the rice self-sufficiency scenarios we calculated what is needed to make production match consumption. We added to each production term a possible change in average yield and production area (Δ)

$$C_{milled} = 0.65 \times [(HA_{rf} + \Delta HA_{rf}) \times (Y_{a_{rf}} + \Delta Y_{rf}) + (HA_{ir} + \Delta HA_{ir}) \times (Y_{a_{ir}} + \Delta Y_{ir})] \quad (4)$$

Once three of the Δ s are fixed, the fourth can be calculated, for example ΔHA_{ir} becomes

$$\Delta HA_{ir} = [C_{milled}/0.65 - (HA_{rf} + \Delta HA_{rf}) \times (Y_{a_{rf}} + \Delta Y_{rf})] / (Y_{a_{ir}} + \Delta Y_{ir}) - HA_{ir} \quad (5)$$

Laborte et al. (2012), based on Koning and van Ittersum (2009), identify five ways to close the production gap: (1) expansion of land under cultivation, (2) intensification on existing farmland by growing two or three crops a year, (3) narrowing the yield gap in farmers' fields through introducing new technologies, (4) raising the yield ceiling by introducing higher-yielding cultivars, and (5) reducing postharvest losses. We consider options 1–3 here, where option 1 is physical area expansion and options 2 and 3 are intensification options.

Harvested area can be larger than physical area because in some areas two rice crops can be grown in the same field in one year. A national weighted average rice cropping intensity CI_{ir} was calculated weighted by areas under single and double rice cropping (see Section 2.2). For example, if $CI_{ir}=1.6$ then 60% of the farmers' fields will have two rice crops per year and 40% one rice crop per year. For a given value of CI_{ir} we can convert harvested area expansion (ΔHA_{ir}) into physical area expansion (ΔA_{ir})

$$\Delta A_{ir} = \Delta HA_{ir} / CI_{ir} \quad (6)$$

For rainfed systems a similar equation ($\Delta A_{rf} = \Delta HA_{rf} / CI_{rf}$) can be applied. However, our data indicated no double rice cropping in any of the rainfed rice areas, so a value of $CI_{rf}=1$ was used for all estimations of rainfed rice production. In the irrigated rice areas, CI_{ir} ranged from 1 to 2. There is anecdotal evidence of farmers growing three rice crops per year, but considering the tight pressure that this puts on logistics and need to grow other crops, we do not consider triple rice crops a realistic option on a large scale. In Egypt, minimum temperatures are often below 15 °C from November to April (6 months). High levels of cold sterility can be expected at those temperatures, so intensification by shifting from one to two rice crops per year on the same land is not possible. Therefore for Egypt we did not allow CI_{ir} to increase. We assumed that intensification on existing farmland would only be possible on irrigated land in the tropical zone in African countries, and to a maximum of two crops per year (except Egypt for which $CI_{ir}=1$). Thus the maximum expansion of harvested area rice on existing irrigated rice land can be calculated as:

$$\text{Max}\{\Delta HA_{ir}\} = A_{ir} \times (2.0 - CI_{ir}) \quad (7)$$

Likewise we constrained maximum yield increases ΔY_{rf} and ΔY_{ir} within biophysically and economically realistic bounds

$$\text{Max}\{\Delta Y_{rf}\} = (0.8 \times Y_{w_{rf}}) - Y_{a_{rf}} \quad (8)$$

$$\text{Max}\{\Delta Y_{ir}\} = (0.8 \times Y_{p_{ir}}) - Y_{a_{ir}} \quad (9)$$

We assumed that Ya_{rf} cannot increase to more than 80% of its climatic potential Yw_{rf} and similarly 80% of Yp_{ir} for Ya_{ir} (Cassman, 2001; Cassman et al., 2003; Lobell et al., 2009). In general, it is thought that the costs of increasing yields above 80% of yield potential generally do not outweigh the returns. In the scenario analyses, if yield increases from Ya_{rf} to $0.8Yw$, Ya_{ir} to $0.8Yp$, and expansion of HA_{ir} through greater double cropping to $A_{ir} \times (2.0 - CI_{ir})$ results in rice production less than requirements, then rice self-sufficiency can only be achieved through area expansion. To calculate if and how much extra area would be needed, we increased cropping intensity and yields (constrained by Equations (7), (8) and (9)) and then calculated how much extra area, rainfed or irrigated, would be needed. Because in many countries yields are still far below 80% of the climatic potential, we also considered scenarios of more modest and feasible yield increases (Saito et al., 2012, 2013; Haefele et al., 2013), increasing Ya_{rf} and Ya_{ir} by 1.0 t ha^{-1} and 2.0 t ha^{-1} , respectively (while not allowing yields to increase above the 80% level). These yield increases between 2012 and 2025 are equivalent to 77 and $156 \text{ kg ha}^{-1} \text{ year}^{-1}$ of yield grow rate, respectively. We also considered the scenarios of no yield increase (most pessimistic scenario) and the scenario in which we extrapolated from the annual rate of yield increase from 2007 to 2012.

In the following sections we describe how yields, areas, and current and future consumption were estimated.

2.2. Site selection and yields

Rationale and justification for the protocols used for collection and sources of yield, soil, and weather data, and for simulation and aggregating results to the national level are described in van Ittersum et al. (2013) and Van Wart et al. (2013a, 2013b, 2013c). Additional details on methods for selecting sites, calculating yields, and aggregating these to the national level are available on the GYGA website (GYGA, 2014). Here we describe the approach briefly.

Sites were selected using the Spatial Production Allocation Model (SPAM) land cover map (You and Wood, 2006; You et al., 2009), which distinguishes between irrigated and rainfed harvested crop areas. Weather stations were selected in major rice production regions and a buffer zone with a 100 km radius around each weather station was drawn using ArcGIS software. The number of buffer zones was such that total harvested rice area in the buffer zones covered at least 50% of the total national harvested rice area according to SPAM. In total 22 stations for irrigated rice and 29 for rainfed rice were selected. Within each buffer zone the relative share of rainfed upland, rainfed lowland, and irrigated areas, the share of land under single and double rice cropping, sowing dates and length of growing period for single and double crops, and recent actual yields Ya for each cropping period were estimated using data from Africa Rice Center, its partners, and collaborators in the GYGA project. Yp and Yw were simulated with a modified version of the ORYZA2000 model (Bouman et al., 2001). The model was adapted because the existing model overestimated heat sterility in semi-arid conditions as found in some African countries (Julia and Dingkuhn, 2012, 2013; van Oort et al., 2014). Location-specific simulated yields and observed actual yields from each weather station were aggregated to buffer zone, climate zone, and national level, weighted for the harvested area within the buffer zone and climate zone, respectively.

As input data for the model we used information on actual sowing dates and lengths of growing seasons specific for each site and system. We identified one major rice cultivar grown in each site and production system and then fixed crop duration of the cultivar in the simulations, since phenology parameters are not available for running the model. The model uses as input

daily weather data: minimum and maximum temperature, radiation, rainfall, wind speed, and early morning vapor pressure. Weather data were obtained from various sources and in some cases datasets were combined to create 10–20 years continuous time series (GYGA, 2014). Yields were simulated separately for each year and then averaged over all years for which weather data were available. While no soil data are required to simulate yields with irrigation because it is assumed that water is available in adequate supply throughout the growing season, rice simulation under rainfed conditions requires data on soil properties that govern water balance. Rice has a shallow root system (max. 40 cm) and greater sensitivity to drought than most crops, which means it is less dependent on how much water can be stored in soil and more dependent on the rate at which water enters the soil (from rainfall, irrigation, and net run-on) and leaves the soil (drainage, evapotranspiration, and net run-off). A sensitivity analysis of simulated yields as a function of several soil parameters identified groundwater table depth, percolation rate, presence of a plow pan, and puddling as the most important soil properties, which is consistent with previous studies (Bouman et al., 1994; Wopereis et al., 1994). To our knowledge, however, no global or national databases with data required to quantify these soil properties exist, even within international databases such as ISRIC (Batjes, 2012). Because of this lack of data, generic soil properties typical of many regions where rice is grown were assumed, one for upland soils and one for lowland soils. For both soils we assumed a soil water retention curve and hydraulic conductivity curve typical for a more clayey soil, for both we assumed no hardpan present and no puddling. Key differences were in the assumptions on groundwater level (lowland: 0.2 m, upland: 10 m), percolation rate (lowland: 4 mm day^{-1} , upland: 240 mm day^{-1}) and bunds (lowland: 25 cm, upland: 0 cm).

2.3. Harvested rice area

Harvested rice area was obtained from the USDA production, supply and distribution database (USDA, 2014) for the most recent year (2012), which we use as the baseline. According to this database, on average over the whole of Africa harvested rice area has expanded substantially since 2000, by 32% (Figure 1). The USDA database contains only total harvested area at a national level and does not distinguish between rainfed and irrigated areas. To estimate the fractions of irrigated and rainfed areas, we used areas of rainfed and irrigated rice from the SPAM map (You and Wood, 2006; You et al., 2009), which is based on land cover data (year 2000) and other sources. These were multiplied by our estimates of cropping intensity (CI_{rf} and CI_{ir}) in each buffer zone to obtain the proportion of total harvested rice area that is rainfed or irrigated. For future scenarios, we assumed these fractions did not change over time. Total harvested area of rainfed rice in 2012 (HA_{rf} , Eq. (1)) was thus calculated as total harvested area rice in 2012 (USDA) \times fraction harvested area rainfed (SPAM) and likewise for irrigated area.

2.4. Consumption

Current per-capita rice consumption by country was calculated from 2012 consumption (USDA, 2014) and population (UN, 2014). On average, per-capita consumption has more than doubled in Africa, from 12 kg year^{-1} in 1960 to 27 kg year^{-1} in 2012, which is still low in comparison with the average of 103 kg year^{-1} for Asia (Mohanty, 2014). Great variation exists, however, from 3 kg year^{-1} in Zambia to 105 kg year^{-1} in Mali (Table 1). For the scenarios for the year 2025 we assumed population growth would follow the UN medium population growth variant (UN, 2014). The SSA population in 2100 is projected to become 6 times as large as in 2000 (Figure 1d). For

Table 1. Rice self-sufficiency for current consumption under different production scenarios.

	Consumption (Mt) in 2012	Production (Mt) in 2012	Imports (Mt) in 2012	Production/ consumption (P/C)	Consumption ^a (kg person ⁻¹ year ⁻¹)	
					2012	2025
Burkina Faso	0.64	0.32	0.32	0.49	25	35
Ghana	1.46	0.24	1.22	0.16	37	45
Mali	2.39	2.14	0.25	0.89	105	156
Nigeria	9.13	4.81	4.32	0.53	35	44
Tanzania	1.69	1.41	0.28	0.83	23	24
Uganda	0.27	0.27	0	0.99	5	5
Zambia	0.06	0.04	0.02	0.57	3	5
Egypt	6.00	7.10	-1.1	1.18	48	51
Total	21.65	16.32	5.33	0.75		
Tot. excl. Egypt	15.65	9.22	6.43	0.59		

Sources: a. USDA (2014) and UN (2014).

2025 relative to 2012, population for SSA is expected to increase by a factor 1.39. For the countries included in this study, population is expected to increase by between factors of 1.2 (Egypt) and 1.52 (Zambia).

To calculate future rice consumption, we multiplied population by per-capita consumption. In one set of scenarios we assumed no change in diet, in the other set of scenarios we extrapolated per-capita consumption from the trend in the period 2000–2012. In this period per-capita consumption increased by 7–9% per year in Burkina Faso, Mali, and Zambia, 4–5% in Ghana and Nigeria, and 0% in Egypt, Tanzania, and Uganda.

2.5. Scenarios

The future for yield increase is uncertain, as is the future for diet change. Both are in part dependent on autonomous development and to in part they may be influenced by policy makers. For example, increased investments in subsidies on inputs (seeds, fertilizer, pesticides, etc.) can lead to increased yields. To cope with uncertainties in future yield and diet change we included a range of scenarios for yield increase and a two scenarios for diet change. In the most pessimistic scenario, yields would stagnate. In the middle scenarios yields would continue to increase following the trend since 2007 (Table 2). These trends are of a similar order of magnitude as the scenarios of 1 or 2 t ha⁻¹ of yield increase from 2012 to 2025, which corresponds with average trends of 78 or 156 kg ha⁻¹ year⁻¹. These two yield trends are lower and higher than the recent yield trend in SSA of about 100 kg ha⁻¹ year⁻¹ since 2007 (Seck et al., 2013). In SSA, even with a 1 or 2 t ha⁻¹ yield increase, the yields would still be far below the biophysical maximum (Figure 3). At the biophysical and economic extreme end of the spectrum yields could be increased to 80% of potential (*Yw* or *Yp*).

3. Results

3.1. Current situation

On average over all simulated sites, all cropping patterns (wet or dry season cropping), and all production systems, actual yields are only 38% of their potential and within a range of 10–70% except for the Nile Delta in Egypt, where actual yield is about 80% of *Yp* (Figure 3). In SSA, actual yields in rainfed systems range from 1 to 3 t ha⁻¹, while actual yields in irrigated systems range from 2 to 6 t ha⁻¹. In irrigated systems, actual and potential

Table 2. Recent yield trend and yield trend needed to achieve 80% of the potential.

	Yield trend 2007–2012 (kg ha ⁻¹ year ⁻¹) ^a	Yield trend needed to get from <i>Y_a</i> to 80% of <i>Y_p</i> or <i>Y_w</i> from 2012 to 2025 (kg ha ⁻¹ year ⁻¹) ^b	
		Rainfed	Irrigated
Burkina Faso	88	254	277
Ghana	169	431	305
Mali	127	198	305
Nigeria	117	295	382
Tanzania	-108	246	306
Uganda ^c	29	211	
Zambia ^c	196	529	
Egypt ^c	-229		-18

Sources: a. USDA (2014). b. GYGA (2014). c. For Uganda and Zambia there are currently no large areas used for irrigated rice production. There is no rainfed agriculture in Egypt.

yields are higher in the dry season than in the wet season. Relative yields (*Y_a*/*Y_w* for rainfed and *Y_a*/*Y_p* for irrigated) are lowest in the rainfed upland and lowland (average 0.27), followed by irrigated lowland in the wet season (0.4), and irrigated lowland in the dry season (0.55).

The production–consumption ratios (*P/C*) in 2012 ranged from 0.16 to 1.18 in the eight African countries (Table 1). Egypt is more than self-sufficient, and Mali, Tanzania, and Uganda are close to being self-sufficient (Table 1). In contrast, Burkina Faso, Ghana, Nigeria, and Zambia are far from being self-sufficient. Table 2 and Figure 1 show high rates of yield increase since 2007. These rates of yield increase are still far lower than in the scenario where yields in 2025 are at 80% of *Y_w* or *Y_p* (Table 2). To achieve yields of 80% of *Y_w* or *Y_p* by 2025 would require a significant acceleration relative to the current yield trend (Table 2). It is questionable whether this is realistic to expect.

3.2. Scenarios 2025

The trade-off between area used for rice and imports, based on Tables 1–5, is shown in Figure 4. The black dot in the middle is the situation in 2012. We describe Burkina Faso as an example. The left pane shows that at current yield trends and unchanged diet, imports or area would need to increase a bit (blue line). In case

of no area expansion, imports would increase from 0.32 Mt/year (Table 1) to 0.42 Mt/year (Table 3) or in case of striving for full self-sufficiency, area would need to increase. Table 5 shows that either rainfed area would need to increase from 87 to 248 thousand hectares or irrigated area increase from 33 to 87 thousand hectares. For Burkina Faso with the current yield trend and increased per capita consumption (from 25 to 35 kg/person/year, Table 1), large increases in area and/or imports would be needed (red line). Thus diet changes can have a large impact on projections of future import and area needs (red vs. blue line). In 2012 the Burkina Faso P/C ratio was 0.49, indicating a high dependence on imports (Table 1, Figure 4 right pane). If for political or economic reasons a higher P/C ratio is desired then the

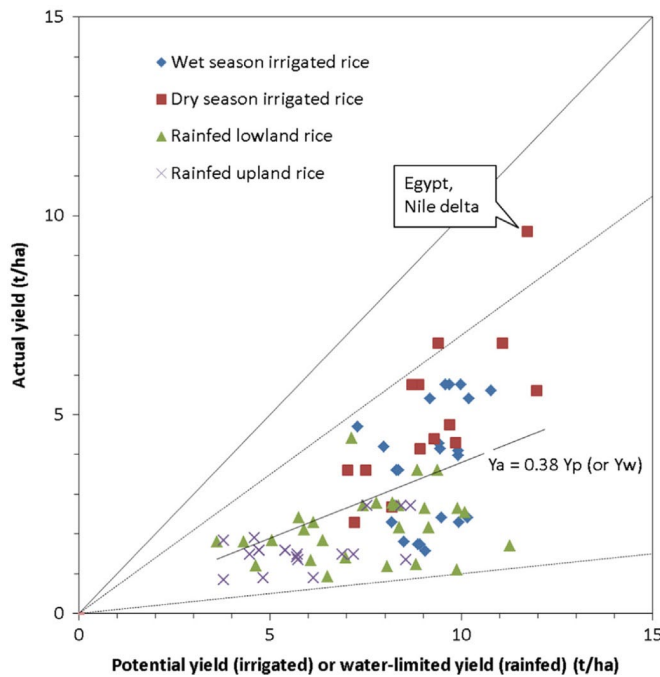


Figure 3. Simulated and actual yields for all sites in Africa simulated in the Global Yield Gap Atlas (GYGA) project. Lines shown are the 1:1 line, relative yields at 10% and 70% of potential yields, and the regression line through all data points.

associated extra area can be looked up in Figure 4 in the right pane. For example a P/C ratio of 0.8 can be achieved by increasing irrigated area from 0.033 Mha to around 0.065 Mha (blue line) or 0.100 Mha (red line). The green and purple graphs in Figure 4 show the trade-off between area and imports or P/C ratios in case yields are increased to 80% of the biophysical potential.

The right panes in Figure 4 show how self-sufficiency in relative terms would change under different scenarios of yield increase and change in area, for all the 8 countries. With current rates of yield increase, none of the countries can become fully self-sufficient in rice without area expansion (Figure 4, red and blue lines). With maximally accelerated rates of yield increase over 2012–2025, five countries could become net exporters (Figure 4, green and purple lines). For Burkina Faso, Ghana, Nigeria and Zambia, which are far from being self-sufficient in rice in 2012, self-sufficiency ratios would still remain below far below one at current yield trends. For Mali, Tanzania and Uganda, close to being self-sufficient in rice in 2012, the scenarios differ between countries. For Mali, self-sufficiency would stay the same in case of no diet change; self-sufficiency would strongly decrease in case of diet change. For Tanzania and Uganda projected changes in diet are small. Under both scenarios, self-sufficiency would dramatically decrease. But with rates of yield increase of 1 t/ha, these two countries could still remain self-sufficient without additional area expansion (Table 4). Egypt was a net exporter in 2012 (Table 1: $P/C=1.18$). With projected population increase and no change in rice area, the country would change into a small net importer (Table 4: $P/C=0.92-0.99$).

Although full self-sufficiency may not be economically optimal, or politically realistic, the analysis of the extra required area in the extreme case of full self-sufficiency provides an indication of how much extra area would be needed at most. Rainfed area would need to become on average over the eight countries 2.5 times as large (Table 5: 7562/2990), ranging between 1.4 in Uganda and Zambia to 4.3 in Burkina Faso and Ghana. If expansion were to come from irrigated area only, irrigated area would on average need to expand by a factor 2.5 (3.4 excluding Egypt), ranging between 1.1 in Egypt to 19.2 in Ghana. The required relative expansion in Ghana from irrigated land is large because there is relatively little irrigated land, so irrigated land contributes very little to total production. For Burkina Faso, Ghana,

Table 3. Imports for scenarios 2025 with no area expansion. (Mt rice at 14% moisture)

	Current diet						Diet extrapolated based on trend 2000–2012					
	No yield increase	Y trend '07–'12	Yield +1 t ha ⁻¹	Yield +2 t ha ⁻¹	Yield to 80% of Y _p or Y _w	80%+ double crop	No yield increase	Y trend '07–'12	Yield +1 t ha ⁻¹	Yield +2 t ha ⁻¹	Yield to 80% of Y _p or Y _w	80%+ double crop
Burkina Faso	0.60	0.42	0.45	0.29	0.07	0.07	0.95	0.77	0.79	0.64	0.42	0.42
Ghana	1.64	1.26	1.47	1.30	0.72	0.68	2.04	1.66	1.87	1.70	1.11	1.08
Mali	1.46	0.38	0.81	0.16	-0.79	-2.85	3.20	2.13	2.55	1.90	0.96	-1.11
Nigeria	8.16	4.73	3.66	3.66	-1.36	-7.14	11.59	8.15	7.09	7.09	2.07	-3.71
Tanzania	1.04	1.04	0.09	-0.86	-2.05	-2.20	1.17	1.17	0.22	-0.73	-1.93	-2.07
Uganda	0.14	0.09	0.00	-0.14	-0.24	-0.24	0.15	0.10	0.01	-0.13	-0.23	-0.23
Zambia	0.06	-0.02	0.03	0.00	-0.15	-0.15	0.12	0.05	0.09	0.06	-0.08	-0.08
Egypt	0.10	0.10	0.10	0.10	0.28	0.28	0.47	0.47	0.47	0.47	0.64	0.64
Total	13.20	8.02	6.61	4.52	-3.52	-11.54	19.69	14.50	13.09	11.00	2.96	-5.06
Total excl. Egypt	13.10	7.91	6.51	4.41	-3.80	-11.82	19.22	14.03	12.63	10.53	2.32	-5.70

No yield increase=yields fixed to levels as reported in the GYGA project; Y trend '07–'12=yields from GYGA-projected increase following annual national trend from 2007 to 2012 derived from USDA (2014); Yield +1 t ha⁻¹=all yields from GYGA increased by 1 t ha⁻¹; Yield +2 t ha⁻¹=all yields from GYGA increased by 2 t ha⁻¹; Yield to 80%=yields increased to 80% of the biophysical potential (Y_w or Y_p); 80%+double crop=yields increased to 80% of the biophysical potential and cropping intensity on irrigated land increased from current CI_{ir} to $CI_{ir}=2$ (except for Egypt: $CI_{ir}=1$).

Table 4. Production/consumption (P/C) for scenarios 2025 with no area expansion.

	Current diet						Diet extrapolated based on trend 2000–2012					
	No yield increase	Y trend '07–'12	Yield +1 t ha ⁻¹	Yield +2 t ha ⁻¹	Yield to 80% of Y_p or Y_w	80%+ double crop	No yield increase	Y trend '07–'12	Yield +1 t ha ⁻¹	Yield +2 t ha ⁻¹	Yield to 80% of Y_p or Y_w	80%+ double crop
Burkina Faso	0.35	0.54	0.51	0.68	0.92	0.92	0.25	0.39	0.37	0.50	0.67	0.67
Ghana	0.13	0.33	0.22	0.31	0.62	0.64	0.10	0.27	0.18	0.25	0.51	0.52
Mali	0.59	0.89	0.78	0.96	1.22	1.79	0.40	0.60	0.52	0.64	0.82	1.21
Nigeria	0.37	0.64	0.54	0.72	1.10	1.55	0.29	0.50	0.43	0.57	0.87	1.23
Tanzania	0.57	0.57	0.96	1.35	1.84	1.90	0.55	0.55	0.91	1.28	1.75	1.80
Uganda	0.65	0.78	1.00	1.34	1.59	1.59	0.63	0.76	0.97	1.30	1.55	1.55
Zambia	0.38	1.18	0.69	1.01	2.54	2.54	0.22	0.70	0.41	0.60	1.51	1.51
Egypt	0.99	0.99	0.99	0.99	0.96	0.96	0.94	0.94	0.94	0.94	0.92	0.92
Total	0.55	0.73	0.70	0.85	1.12	1.39	0.45	0.60	0.57	0.69	0.92	1.14
Total excl. Egypt	0.41	0.65	0.61	0.80	1.17	1.53	0.32	0.51	0.48	0.63	0.92	1.20

No yield increase=yields fixed to levels as reported in the GYGA project; Y trend '07–'12=yields from GYGA-projected increase following annual national trend from 2007 to 2012 derived from USDA (2014); Yield +1 t ha⁻¹=all yields from GYGA increased by 1 t ha⁻¹; Yield +2 t ha⁻¹=all yields from GYGA increased by 2 t ha⁻¹; Yield to 80%=yields increased to 80% of the biophysical potential (Y_w or Y_p); 80%+double crop=yields increased to 80% of the biophysical potential and cropping intensity on irrigated land increased from current CI_{ir} to $CI_{ir}=2$ (except for Egypt: $CI_{ir}=1$).

Table 5. Required physical area (ha×1000) for full rice self-sufficiency with projected population in the year 2025.

	Existing rainfed physical area	Rainfed area needed ^a with irrigated rice area unchanged				Existing irrigated physical area	Irrigated area ^{and} with rainfed rice area unchanged			
		'07-'12 rate of yield increase, current cropping intensity		yields increased to 80% of Y_p or Y_w and CI_{ir} =2			'07-'12 rate of yield increase, current cropping intensity		yields increased to 80% of Y_p or Y_w and CI_{ir} =2	
		Current diet	Current +trend	Current diet	Current +trend		Current diet	Current +trend	Current diet	Current +trend
Burkina Faso	87	248	379	102	174	33	87	131	39	66
Ghana	152	524	641	258	316	11	164	212	60	89
Mali	238	319	686	99	406	346	410	700	152	271
Nigeria	1465	2805	3777	1232	1819	785	1989	2862	300	533
Tanzania	878	1746	1853	411	440	44	174	190	0	0
Uganda ^c	140	178	184	88	90					
Zambia ^c	30	25	43	12	20					
Egypt ^c						740	751	788	770	809
Total	2990	5845	7562	2201	3266	1960	3575	4883	1322	1768
Total ex Egypt	2990	5845	7562	2201	3266	1220	2824	4095	552	959
Total/current		2.0	2.5	0.7	1.1		1.8	2.5	0.7	0.9
Total excl. Egypt/current		2.0	2.5	0.7	1.1		2.3	3.4	0.5	0.8

a. Note the table shows total area needed, not extra area needed. For example if only rainfed area expands, yields increase at the '07–'12 rate and diet remains unchanged, then for Burkina Faso in total 248×1000 ha rainfed rice area would be needed to achieve full self sufficiency. That would mean the rainfed rice area would increase by a factor 248/87=2.9 and the extra area needed would be (248–87)×1000 ha=161×1000 ha.

b. For irrigated rice we first calculated existing harvested area+expansion (Equation (5)) and from that physical area (Equation (6)).

c. For Uganda and Zambia there are currently no large areas used for irrigated rice production. There is no rainfed agriculture in Egypt.

Mali, Nigeria, and Tanzania, rice physical area in 2025 would need to more than double to achieve self-sufficiency.

4. Discussion

Yield gap assessment for rice production in eight African countries coupled with analysis of current and future rice production-consumption scenarios led to the following conclusions: (1) the production-consumption ratios (P/C) in 2012 ranged from 0.16 to 1.18. One country was more than self-sufficient, three were close to being self-sufficient and four countries are far from being

self-sufficient in rice (2) there are large yield gaps between potential and actual yields except for Egypt; (3) with the current trends in yield, consumption, and population growth, none of countries can achieve rice self-sufficiency in 2025 without additional area expansion; (4) even with raising rice yield level to 80% of the potential and with double cropping in irrigated systems, self-sufficiency cannot be achieved without area expansion in Burkina Faso, Ghana, and Egypt; (5) for other countries, it is theoretically possible to achieve rice self-sufficiency at a national level in 2025 without area expansion by increasing yields to 80% of their biophysical potential plus double cropping in irrigated systems;

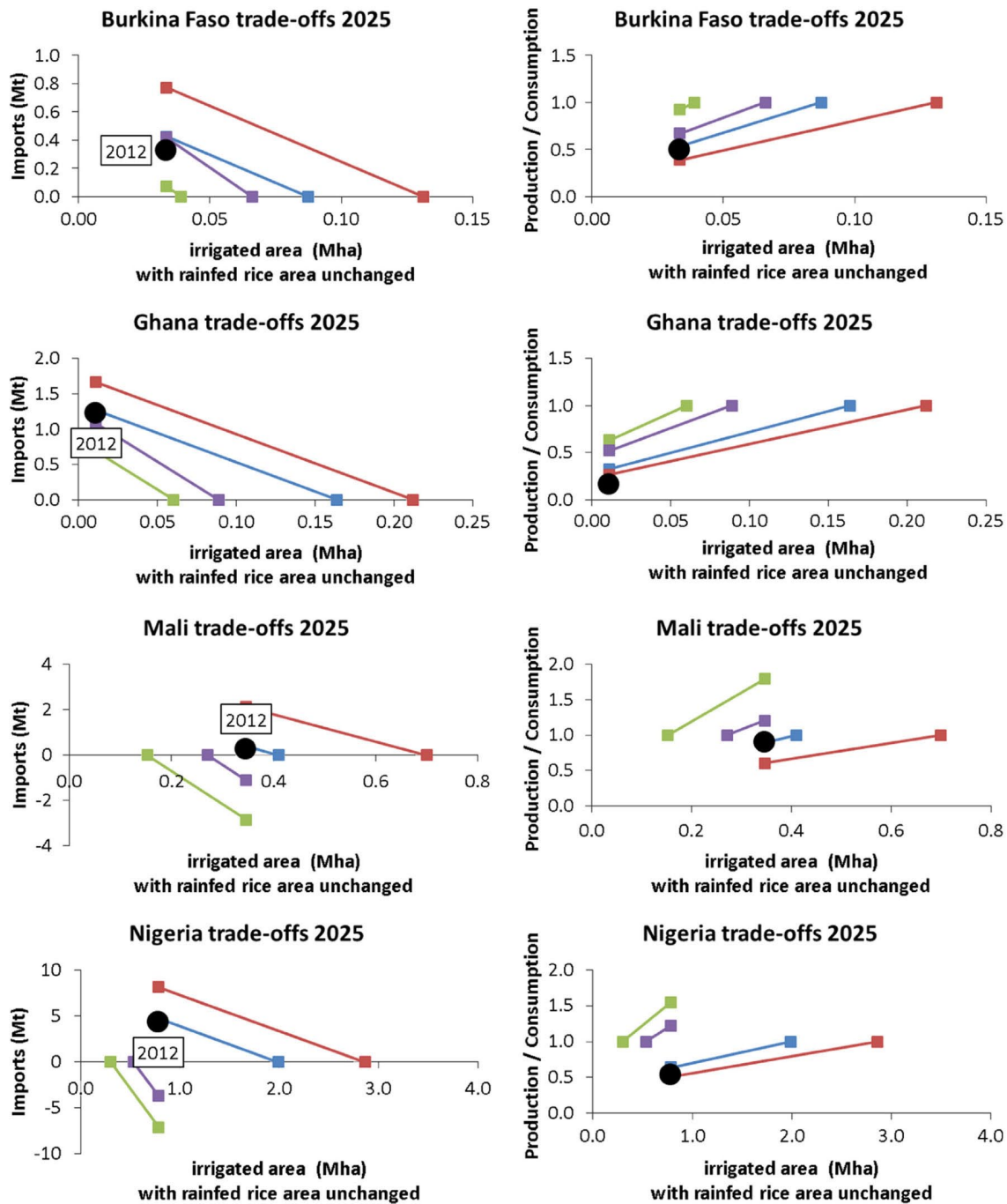


Figure 4. Trade-off between area use and imports (left panes) or self-sufficiency P/C ratio (right panes). The black dot is the situation in 2012. Colored graphs are trade-off curves based on data presented in Tables 1-5: blue = 07-12 rate of yield increase, current cropping intensity, current diet; red = 07-12 rate of yield increase, current cropping intensity, changed diet; green = yields increased to 80% of Y_p or Y_w and $CI_{ir} = 2$, current diet; purple = yields increased to 80% of Y_p or Y_w and $CI_{ir} = 2$, changed diet.

(6) further research is needed on where future expansion of rice production can best take place (7) further economic analysis is needed on the trade-off between area expansion and imports.

Our estimated yield gaps are in the same range of yield gaps in previous studies in Africa (Becker et al., 2003; Hijmans and Serraj; Saito et al., 2013). Yield gap analyses have been criticized for lacking relevance (Sumberg, 2012). As van Ittersum et al. (2013) note, yield gap analysis alone is not enough, complementary research is also needed. It is, for example, of limited relevance to know that at a given location the yield gap is 5 t ha^{-1} . More important is how the yield gap can be closed, which requires on-the-ground research into socioeconomic and

biophysical constraints and solutions (e.g. Haefele et al., 2013; Saito et al., 2012, 2013; Kumashiro et al., 2013; Tanaka et al., 2013; Nhamo et al., 2014) and effective policies (e.g. see Anderson and Masters, 2009; Fuglie and Rada, 2013).

Achieving 80% of biophysical potential yields by 2025 would require much larger growth rates than currently the case (Table 2). Furthermore, they are higher than the rates observed in green revolution period in Asia (Cassman, 1999), and in Egypt (around 250 kg/ha/year over 1985–2003). This previous high yield growth rate in Egypt was attributed to (i) a physically concentrated rice industry; (ii) strong research and extension effort; (iii) policy reform (from the late 1980s) that removed price

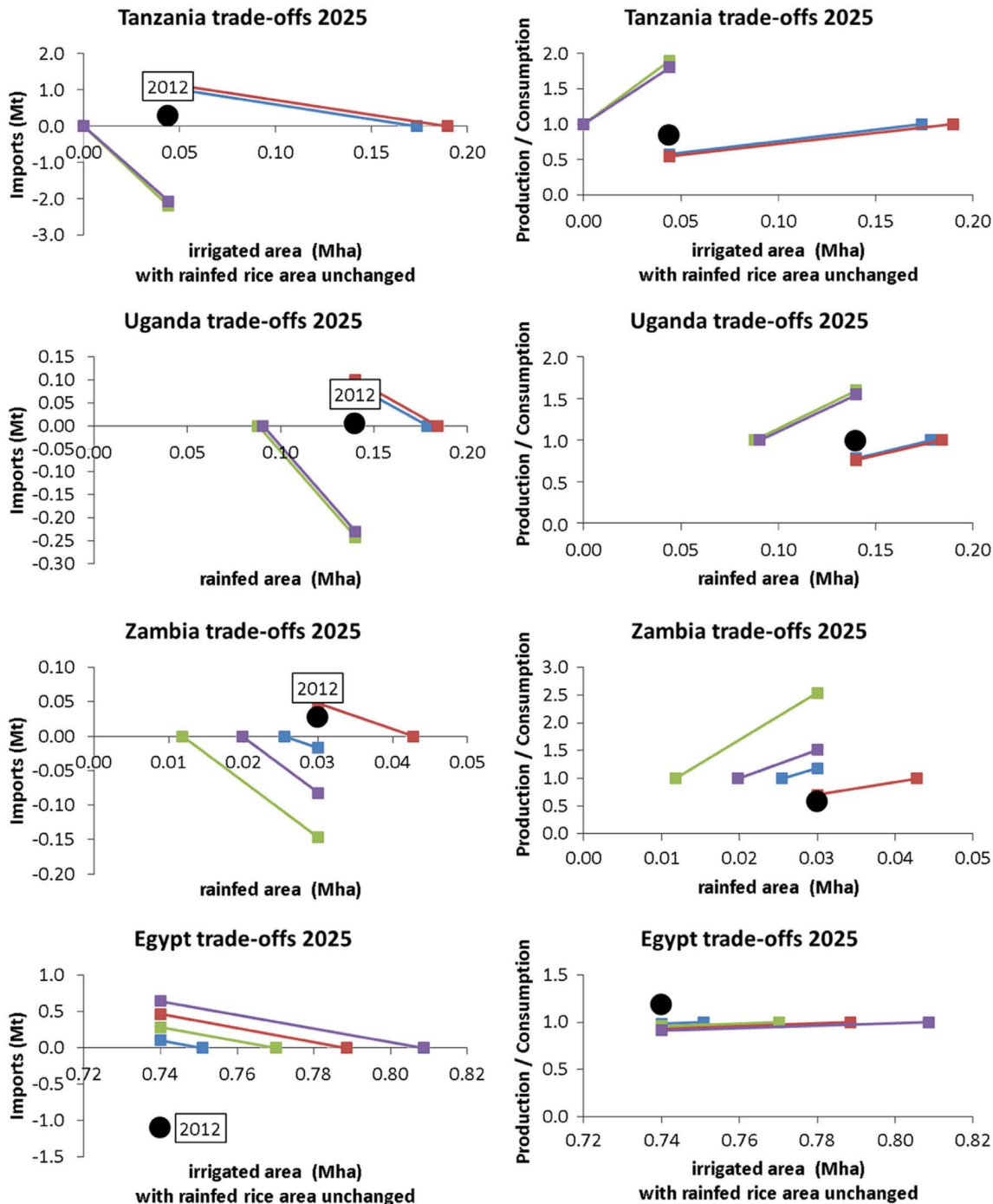


Figure 4. (continued)

disincentives for rice (Cassing et al., 2007). Saito et al. (expecting same volume as this paper) pointed out importance of the share of irrigated rice area for higher yield growth at national level. Thus, as irrigated rice share is still low in most of countries, it is questionable whether it is realistic to expect such accelerated rates of yield increase at national level unless irrigated rice area will be expanded dramatically through upgrading rainfed rice into irrigated rice.

Our analyses revealed that in most of the countries full rice self-sufficiency cannot be achieved if the more modest and probably more realistic scenarios of yield increase come true. As noted, it is not self-evident that every African government should strive for full self-sufficiency in rice (see our conceptual Figure 2 discussed in the introduction). Rather, economic,

societal and political decision making will take place within the biophysical boundaries identified in this paper. Politicians may decide to remain to a greater or lesser degree dependent on imports. If politicians consider future dependence on imports (Table 3) unacceptably high, or future P/C ratios (Table 4) unacceptably low then area expansion or reconsidering targeted yield levels will be needed. This is an important outcome in the context where great ambitions exist to increase rice production (Seck et al., 2012, 2013; <http://www.riceforafrica.org>) and where at the same time there are hopes that this could be achieved without large claims on unused land (Tilman et al., 2002; Cassman et al., 2003; Koning and van Ittersum, 2009; Foley et al., 2011; Pretty et al., 2011; Ramankutty and Rhemtulla, 2012; Garnett et al., 2013; Hall and Richards, 2013).

When the choice is for a certain degree of area expansion, the question arises of how much is available. There exists large uncertainty about how much area is potentially available (Andriessse, 1986; Windmeijer and Andriessse, 1993; Young, 1999; Ramankutty et al., 2002; You et al., 2011; Byerlee et al., 2014). Identification of “unused” areas is not enough. Additional research is also needed on whether rice is biophysically and economically the optimal crop in such “unused” areas. Some studies have estimated potential crop area with water balances and without considering the possibility that two crops per year may be possible if temperatures and irrigation water supply permit. From such studies it remains unclear whether there is also enough water for two crops in potential new irrigation areas and thus they may be underestimating the potential harvested area. Some studies have considered areas as potentially suitable based on soil conditions and rainfall, without considering distance to markets, costs of bringing new areas into cultivation and important soil variables. As a result, for the calculated areas needed for achieving full self-sufficiency in rice (Table 5) we could not verify whether potentially enough area would be available. Therefore, identification of most suitable new land for conversion to rice production as well as identification of areas that should have priority for being protected from conversion to preserve critical natural resources and biodiversity are the first steps towards sustainable area expansion.

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